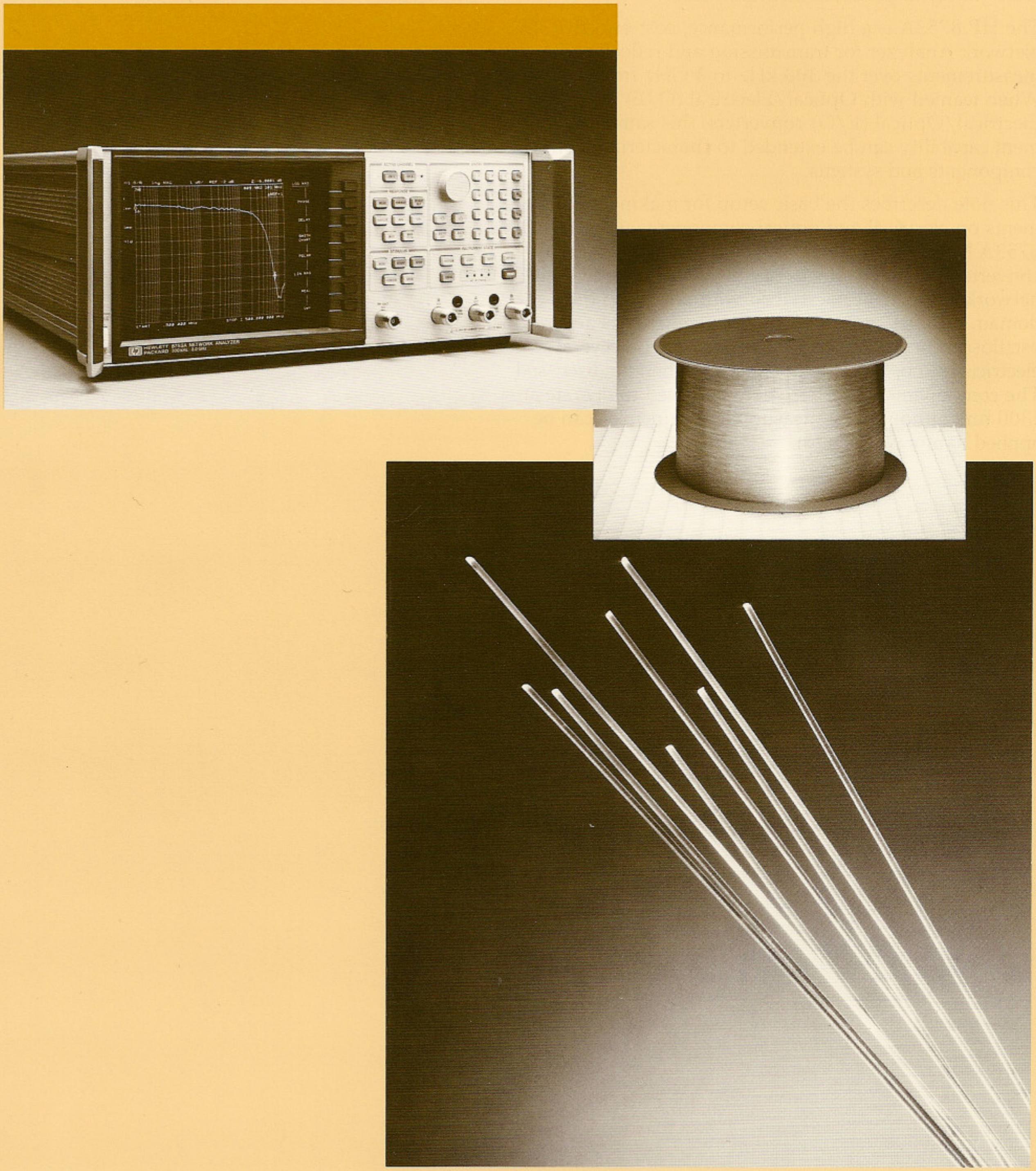
Application Note 351

HEWLETT PACKARD

Fiber Optics
Characterization of High-speed Optical Components with an RF Network Analyzer



Introduction

The last several years have seen a steady move to higher data rates and longer transmission distances in fiber optic systems. With this increased performance comes an increased requirement for high frequency characterization tools. RF Network Analyzers have traditionally been used for years to characterize the amplitude and phase characteristics of linear networks. With the addition of suitable optical converters, network analyzers can also be used for a wide variety of photonic measurements.

The HP 8753A is a high performance, cost-effective RF Network Analyzer for transmission and reflection measurements over the 300 kHz to 3 GHz frequency range. When teamed with Optical/Electrical (O/E) and Electrical/Optical (E/O) converters, this same measurement capability can be extended to characterizing optical components and systems.

This note describes the basic setup for making measurements on electrical and optical components using the HP 8753A Network Analyzer and commercially available converters. The advantages of a swept frequency domain network analyzer are described with respect to time domain analysis tools, such as pulse generators and oscilloscopes. A variety of measurements on several electrical and optical components will then be discussed. The components being tested are designed to operate at 1300 nm, although the measurement principles can be applied to any wavelength.

What is a Network Analyzer?

A Network Analyzer uses a swept frequency source and a tuned, multichannel receiver to make measurements of the transmission and reflection characteristics of devices and networks. The basic block diagram of a Network Analyzer in the transmission configuration is shown in Figure 1. A portion of the source output is sampled and used as a reference for ratio measurements of magnitude and phase. Many useful device characteristics can be derived from the transmitted magnitude and phase. Among these are attenuation or gain, bandwidth, electrical length, and group delay. With the addition of an external directional coupler, reflection measurements can also be made and displayed in many useful formats. These include, return loss, impedance (Smith Chart), and SWR. The optional Time Domain feature allows you to view device characteristics as a function of time, rather than frequency. This is very useful for such measurements as pulse dispersion and fault location.

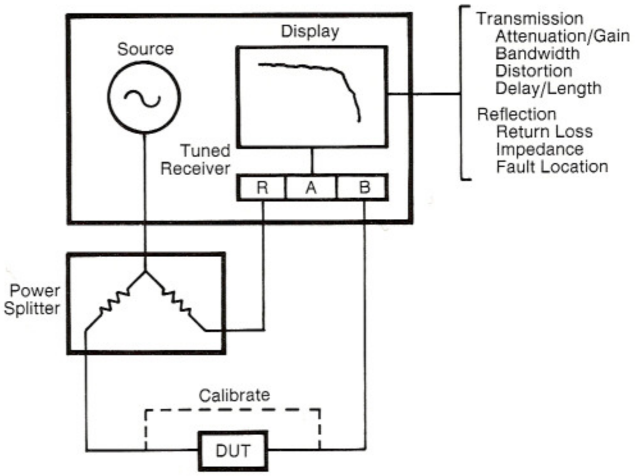


Figure 1. Basic Block Diagram of a Network Analyzer

Network Analyzers also have some very important advantages over traditional time domain tools, such as pulse generators and oscilloscopes. Very high bandwidths are obtainable with network analyzers, allowing measurements to be made on networks with very fast rise times. Because network analyzers are tuned, narrow-band receivers, they have excellent sensitivity and dynamic range. Network analyzers also measure phase, allowing for more complete characterization of networks, and improved accuracy through built-in calibration procedures. In addition, synthesized Network Analyzers can accurately measure phase and group delay even on devices that are electrically long or that have responses which change rapidly with frequency.

Elements of a Photonic Analyzer

With the addition of commercially available converters, a network analyzer can be used for a wide variety of useful electrical and optical measurements. Figure 2 demonstrates the concept of such a Photonics Analyzer. Optical transmission calibration is possible by using a short length of reference fiber with negligible attenuation and dispersion over the frequency range of interest. Likewise, calibrating at the electrical interface allows the system to be used for analysis of electro-optic components and systems. In this case the transmitter and receiver become part of the device under test. Let's discuss each of the elements in our photonics analyzer system in more detail.

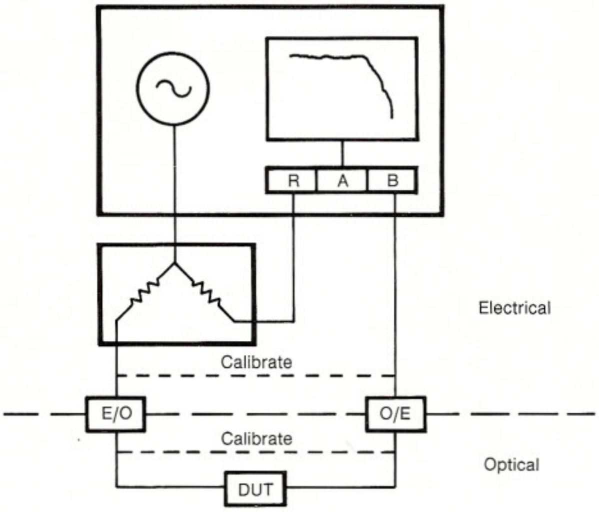


Figure 2. Adding Optical Converters to Create a Photonic Analyzer

The Electrical-to-Optical Converter (E/O) is a device which allows AM modulation to be applied to the lightwave carrier. Laser diode sources are typically used due to their high output power and narrow spectral width, equating to wider dynamic range and broader bandwidth. Modulation is typically applied through direct modulation of the laser drive current, although external modulation using optical or acousto-optical modulators is also an alternative. E/O converters are available for a variety of wavelengths for both single-mode and multi-mode fiber. Single-mode converters, when used with an appropriate mode scrambler (discussed later), can also be used for multi-mode fiber. Important attributes when selecting an E/O Converter are high output power, wide modulation frequency range, flat frequency response, narrow line width, and excellent short term stability.

The Optical-to-Electrical Converter (O/E) is a device which allows an AM modulated lightwave carrier to be detected. The magnitude and phase of the detected envelope contains the baseband response of the network under test. O/E converters are available using both PIN photodiode (PD) and avalanche photodiode (APD) detectors. Avalanche photodiodes typically provide better sensitivity due to internal gains of 50 to 100, but PIN photodiodes offer better linearity and temperature stability. Converters are available for both single-mode and multi-mode fibers in a variety of wavelengths. Important attributes when selecting an O/E converter are wide dynamic range, wide demodulation frequency range, flat frequency response, high maximum input power, and linearity (dynamic accuracy).

An optical directional coupler is a device which is used to separate the incident and reflected signals when making reflection measurements on optical components. Couplers are available in both 1X2 (single directional) and 2X2 (dual directional) configurations and with a broad range of coupling factors. The insertion or "excess" loss of the coupler is a measure of how much the incident signal is attenuated in the main arm and should be low. The coupling factor or "ratio" is a measure of the amount of attenuation experienced by the reflected signal and is normally desired to be low. The isolation or "crosstalk" of the coupler describes the amount of attenuation exhibited by the incident signal as it leaks into the reflected arm, and should thus be high. The difference between the coupling and isolation of a coupler is called the *directivity*, although this term is sometimes used by manufacturers to describe what is actually their isolation. The directivity of the coupler limits the dynamic range available for reflection measurements with a photonic analyzer.

For repeatable multi-mode bandwidth and attenuation measurements, it is important that the input modal distribution be controlled. Without this control, attenuation measurements can vary dramatically due to non-repeatable mode coupling mechanisms as a function of length, such as microbending or ellipticity, particularly with highly coherent sources. This equilibrium of the mode distribution is reached naturally in modern graded-index fibers only after several kilometers. This state is referred to as Equilibrium Mode Distribution (EMD). EMD is defined as a launch numerical aperture (NA) of 70% measured at the 5% intensity levels relative to the fibers' numerical aperture together with a light spot diameter of 70% measured at the 5% intensity levels relative to the core diameter. A mode scrambler also allows single-mode E/O converters to be used on multi-mode fiber measurements.

There are several techniques for establishing an input mode distribution that is spatially and angularly independent of the launch conditions. Among these are mandrel wrapping, use of launch optics, use of a long dummy fiber, and mode scrambling. Mode scramblers are a convenient and inexpensive way of approximating EMD. They typically consist of several alternating sections of fiber exhibiting different core diameters, index profiles, and numerical apertures, butt coupled or fusion spliced together. This arrangement scrambles the input modes spatially and angularly, approximating an EMD condition. When choosing a mode scrambler it is important to have low insertion loss and a mode distribution which is insensitive to source/scrambler misalignment and movement.

How Does This Work?

Refer to Figure 3. In this approach, we are applying direct AM modulation onto the lightwave carrier, and using this as our input signal to the device under test. At 1300 nm, even a 3 GHz modulating signal will produce sidebands less than 1/50th of a nanometer away! These are so close to the lightwave carrier that, for all practical purposes, by measuring the response of the network to the modulated envelope, we are characterizing the response of the network to the carrier.

For multi-mode devices with long lengths, modal effects occur as the modulation frequency increases. By measuring the response of these devices to a swept modulated envelope, we can determine the effect of the network on the information itself, as a function of frequency. This is becoming particularly important as system bit rates rise above 100 MBPS or so.

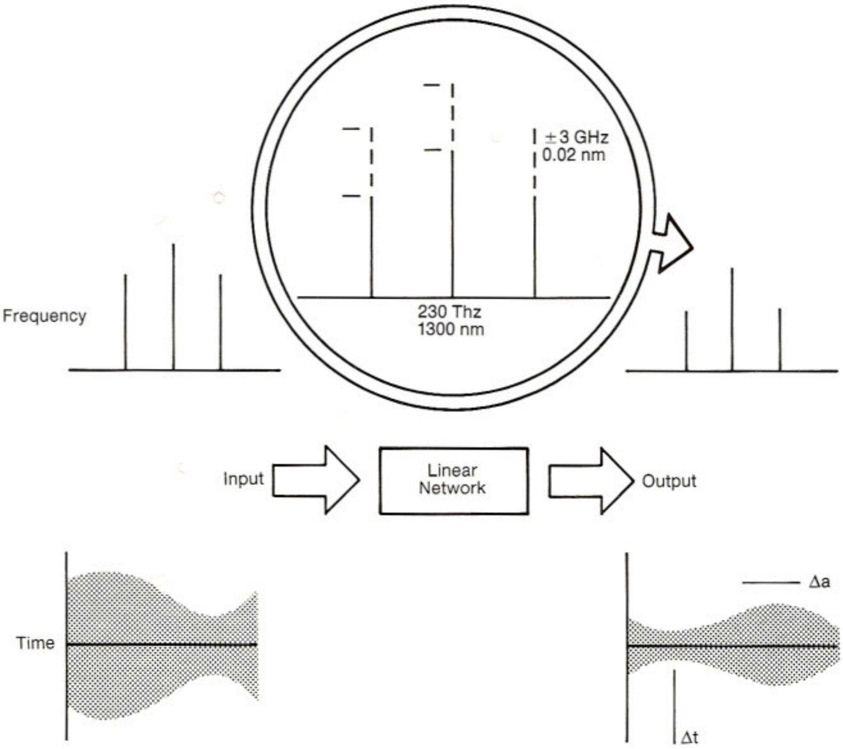


Figure 3. How This Approach Works

The Configuration Used in This Note

Figure 4 shows the photonics analyzer configuration used in this product note. The HP 11667A Power Splitter is used to establish phase-lock and as a reference for ratio measurements. The 1300 nm single-mode E/O converter illustrated uses a laser diode with a 6 nm spectral line width and can be modulated to 1 GHz. The 10 dB attenuator is required to reduce the modulation input power applied to the O/E to an acceptable level. The O/E converter uses an avalanche photodiode with a demodulation frequency range of 1 MHz to 1 GHz. The 1X2 directional coupler has an excess loss of less than 1 dB, a 3 dB coupling factor, and an isolation typically better than 40 dB. The mode scrambler is a GSG-style (Graded-Stepped-Graded) filter consisting of three 1-meter sections of 100 µm core fiber with 140 µm cladding. The scrambler exhibits about 1.5 dB of loss at 1300 nm, and came from the manufacturer without connectors. For this application two FC-PC connectors were fusion-spliced onto the mode scrambler. This system configuration can be used for baseband characterization of 1300 nm multi-mode components and networks. The specific manufacturers and model numbers for these components are summarized in Appendix A at the end of this note.

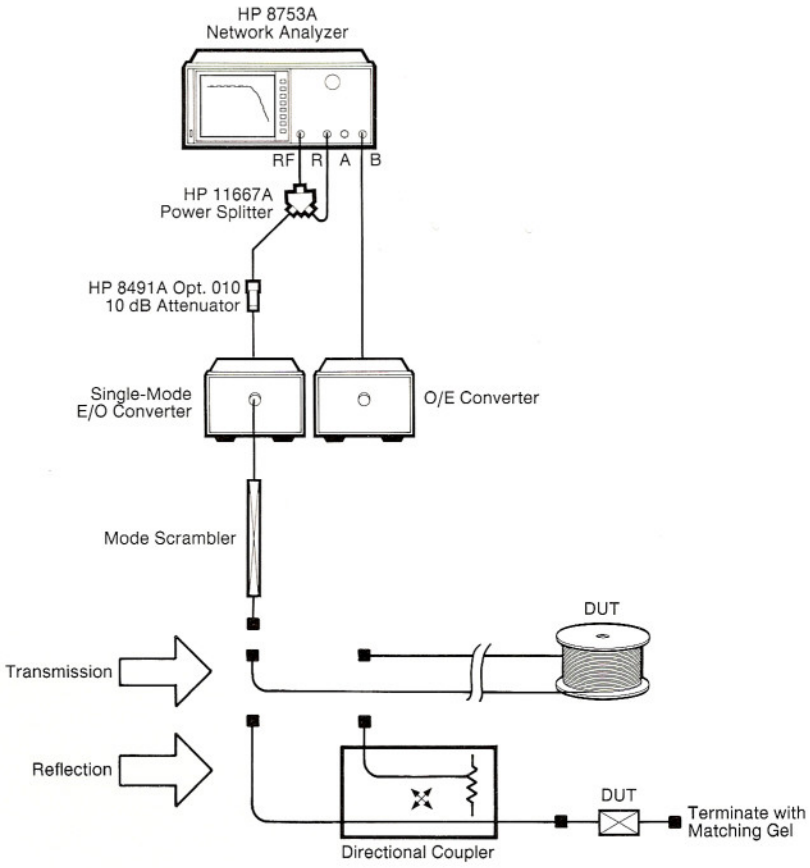


Figure 4. Photonics Analyzer Configuration for 1300 nm Multi-Mode Applications

Typical Measurement Results

The following sections describe several measurements made with the described Photonics Analyzer. Each section includes a description of the measurement, basic setup information, discussion of the results, and important considerations.

Bandwidth

The Measurement. Bandwidth is a measure of the ability of a device or system to transmit high frequency information. The dominant bandwidth-limiting factor in relatively short (<3 km) lengths of multi-mode fiber is typically modal dispersion. Modal dispersion is due to the differential delay between energy propagating in different waveguide modes. Single mode fiber and very long lengths of multi-mode fiber are typically limited by the chromatic dispersion of the fiber over the source spectral line width. Chromatic dispersion is due to the differential delay between signals propagating at slightly different wavelengths.

The Setup. Bandwidth is measured in the transmission configuration by ratioing the transmitted signal (A or B) over the reference signal (R). For optical bandwidth measurements, the system is calibrated using a length of fiber that exhibits negligible loss and dispersion compared to the device under test, typically a short piece of the same fiber being tested. In this case the device under test is a 1.48 km roll of multi-mode fiber with a specified bandwidth-length product of 1113 MHz-km at 1300 nm. A 3 meter section of fiber was used as an optical calibration thru. The HP 8753A output power was set to −10 dBm which sets the modulation drive power to the E/O at −26 dBm when the 16 dB loss of the splitter and attenuator are considered.

Typical Optical Bandwidth Results. Figure 5 shows the frequency response of the fiber. The optical 3 dB bandwidth of this fiber is close to 800 MHz, for a bandwidth-length product of 1142 MHz-km. Marker 1 was placed at the top of the trace with a search feature, and used as a zero reference. Marker 2 was then told to search right for the −6 dB point. The stimulus offset value from marker 1 was then set to 0 to allow us to display the absolute −6 dB frequency.

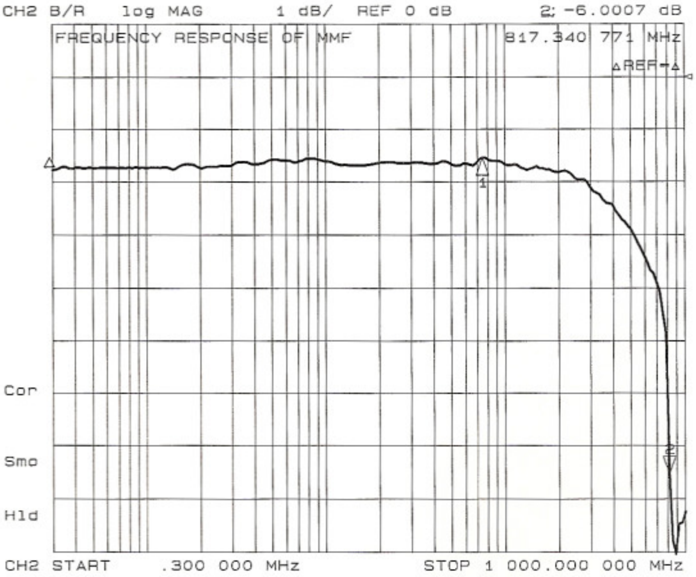


Figure 5. Frequency Response of a 1.5 km Roll of Graded-index Multi-Mode Fiber

Considerations. Network analyzers display electrical power ratios. The indicated −6 dB electrical point corresponds to a −3 dB (half power) optical point. This is can be seen from the transfer function relationship between optical input power and electrical output current in an optical detector:

$$P_{(\text{electrical})} = 10 \text{ Log } \frac{P_1}{P_0}$$

$$= 10 \text{ Log } \frac{I_1{}^2}{I_0{}^2}$$

$$= 20 \text{ Log } \frac{I_1}{I_0}$$

$$\therefore P_{(\text{electrical})} \propto I^2$$

$$P_{(\text{optical})} = 10 \text{ Log } \frac{P_1}{P_0}$$

$$= 10 \text{ Log } \frac{I_1}{I_0}$$

$$\therefore P_{(\text{optical})} \propto I$$

The sweeptime and IF bandwidth must be set carefully on electrically long devices. This is because the receiver continues to sweep while the signal is delayed by the device. The minimum sweeptime for a given device delay is determined by the chosen IF bandwidth, number of points, and frequency span. Here are several representative examples that were empirically determined for a fiber with an index of refraction of 1.5:

IF Bandwidth	Number of Points	Span (MHz)	Minimum Sweeptime (Sec/km)
3 KHz	201	1000	2.0
300 Hz	1601	50	6.0
30 Hz	401	500	4.0

In practice, it is easiest to slow the sweeptime down until a stable trace is obtained (one that doesn't change when the sweeptime is changed).

Typical Electrical Bandwidth Results. Figure 6 shows a similar measurement when the optical transmitter and receiver are included. The system was calibrated at the electrical interface prior to the converters. Another technique for this measurement is to measure the system bandwidth in the time domain, and approximate the optical 3 dB bandwidth assuming a Gaussian system frequency response. It is clear that this system response, as with most containing amplifiers or repeaters, is no longer as strongly gaussian in character as it was for the fiber alone. *By measuring in the frequency domain, we can obtain an accurate picture of the systems' real bandwidth.*

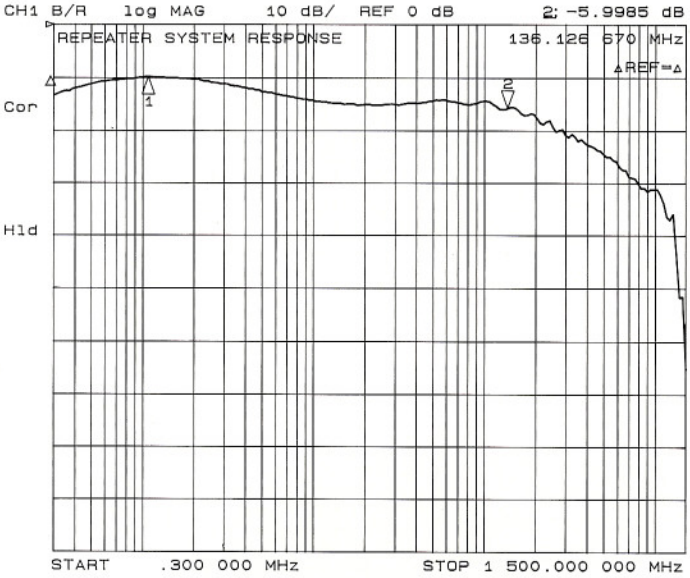


Figure 6. Frequency Response of an Optical System Including Transceivers

Transfer Characteristics

The Measurement. Transfer characteristic measurements include those such as gain, gain compression, sensitivity, and linearity. These measurements can be used to determine the useful dynamic range of devices and systems as well as dynamic (versus power) distortion properties. Devices where this might be important include repeaters and active equalizers.

The Setup. Transfer characteristic measurements are performed in the transmission configuration in either the swept frequency or CW swept power modes. For the swept frequency compression measurement, the system is calibrated at a non-compressed input power level. The non-compressed gain is entered into trace memory and used as a reference using **[DATA/MEM]** trace math. The power is increased until the −2 dB compression point is achieved. The −2 dB electrical gain compression at 555 MHz corresponds to the −1 dB optical compression point.

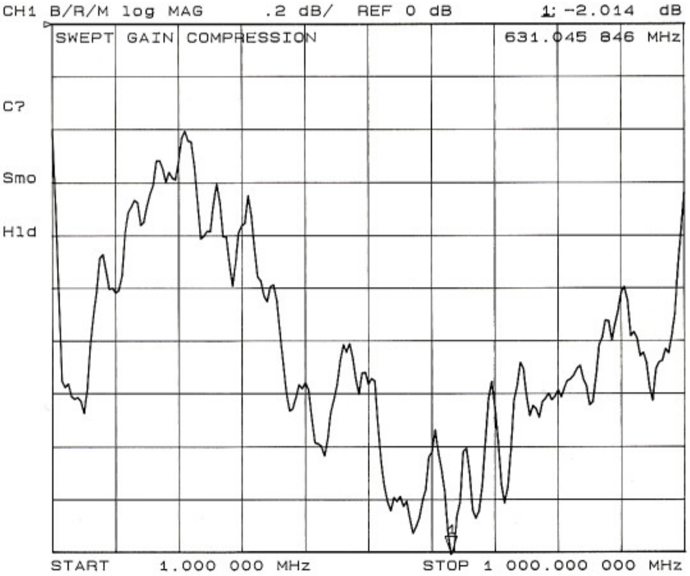


Figure 7. Swept Gain Compression Measurement

Typical Results. Figure 7 shows a swept gain compression measurement on a 1300nm optical transceiver system. The gain compression frequency is approximately 555 MHz, with a corresponding input compression power of −8.5 dBm.

Now that the gain compression frequency has been determined, a more accurate compression measurement is possible in the CW swept power mode. The analyzer output power is set to sweep power, in this case from −10 dBm to +15 dBm at 555 MHz. A response calibration then removes the linearity error of the measurement system, and the device is measured. The linearity of the repeater can also be calculated from this measurement.

Considerations. In these measurements the dynamic accuracy of the network analyzer and the linearity of the optical converters becomes crucial. It is also important to include the effect of the power splitter or test set loss when calculating the actual input power to the device. With appropriate optical attenuators, the same measurement can be used to measure the sensitivity, noise threshold, and dynamic range of the repeater.

Electrical Length

The Measurement. Since a network analyzer can measure phase, it can also be used to measure delay, and hence electrical length. Electrical length can be an important measurement when matching cables, measuring interferometric sensors, or determining the index of refraction of a device. The equivalent electrical length of an optical or electro-optic device can be determined from the swept-frequency transmission phase response of the device. The equivalence of phase, time, and length can be demonstrated by:

$$l_{(electrical)} = \frac{C * \Delta\varphi}{360 * \Delta f}$$

Where: $l_{(electrical)}$ = Equivalent electrical length of DUT in meters of air

C = Speed of light in a vacuum $\cong 3 * 10^8$ m/sec

$\Delta\varphi$ = Change of phase in degrees

Δf = Change of frequency in hertz

The Setup. Electrical length measurements are generally made in the transmission configuration by examining the phase response of the device. The linear phase of the response is removed with the **[ELECTRICAL DELAY]** function of the HP 8753A. The phase response can be either manually flattened with the knob, or automatically flattened using the **[MARKER→DELAY]** feature. A frequency response calibration is performed using a short length of reference fiber to establish a zero-length reference plane.

Typical Results. Figure 8 demonstrates an electrical length measurement on the 1.5 km roll of fiber. This roll of fiber exhibits an equivalent electrical length of 7.2496 microseconds, about 2.1734 km in air. The actual physical length of the device can be calculated if the index of refraction of the fiber is accurately known. The HP 8753A allows the user to adjust the velocity factor used for the length calculation, and thus display the length of the device directly. For most graded and stepped index fibers the velocity factor is entered as 1/n using the **[VELOCITY FACTOR]** feature of the HP 8753A. A velocity factor of 0.667 (1/1.5) was used, giving us a physical length measurement of 1449 meters.

$$l_{(physical)} = \frac{l_{(electrical)}}{n} \qquad \text{(Transmission)}$$

$$l_{(physical)} = \frac{l_{(electrical)}}{2 * n} \qquad \text{(Reflection)}$$

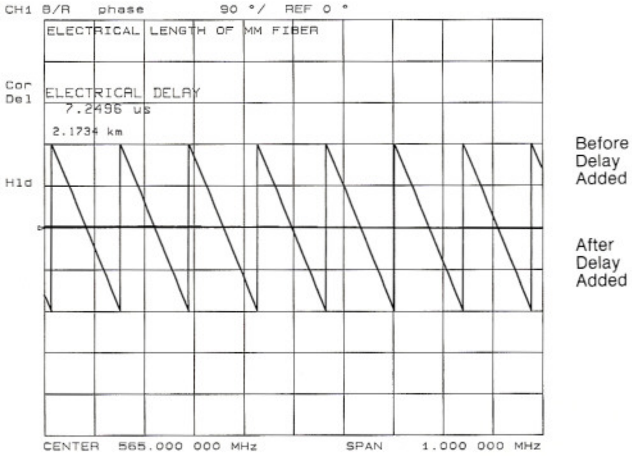


Figure 8. Electrical Length Measurement of a Multi-Mode Fiber

Considerations. With multi-mode fibers it is important to make this measurement over a frequency span where there is negligible modal dispersion, since length is calculated from the linear phase data. With single-mode fiber this is not a problem. Also, for extremely long devices, such as fiber and cable, it is important that the frequency span be narrow enough, and the number of points be high enough that at least two measurements are taken for every 360 degrees of phase rotation through the device.

$$l_{(max)} = \frac{C * (N-1)}{2 * n * Span} \qquad \text{(Transmission)}$$

$$l_{(max)} = \frac{C * (N-1)}{4 * n * Span} \qquad \text{(Reflection)}$$

Where: N = Number of display points

Span = Frequency Span in hertz

In practice, the accuracy of the physical length calculation will be limited by the accuracy to which the devices index of refraction is known. One way to reduce this uncertainty is to measure the phase response of a known length of the same fiber, and use this value for calculating the velocity factor.

Group Delay

The Measurement. Group Delay ripple is derived from the phase ripple induced by a device or system, and can be a very important parameter in a digital system since it may limit system performance by distorting the shape of the digital modulation envelope, thus leading to poorer system Bit Error Rates. Even with the excellent phase linearity of modern graded-index fibers there is the additional distortion of the amplifiers, regenerators, and equalizers to consider.

The Setup. The HP 8753A can display phase distortion as either deviation from linear phase or group delay. This measurement is typically made in the transmission configuration, with a frequency response calibration.

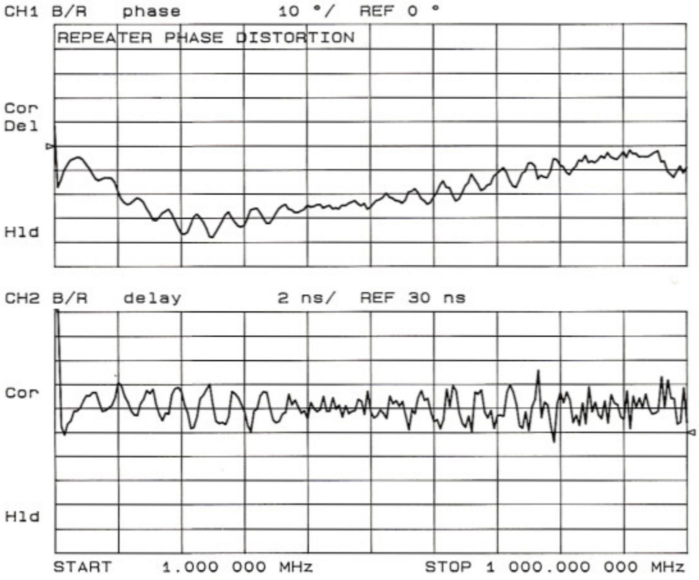


Figure 9. Phase Distortion Represented as Deviation from Linear Phase (TOP) and Group Delay (BOTTOM)

Typical Results. Figure 9 shows the deviation from linear phase and group delay for the transceiver system. Calibration was accomplished using a three meter section of fiber. By removing the linear phase component of the measurement, the phase ripple can be analyzed with better resolution. The group delay is calculated from the phase data as a differential with respect to frequency, and represents the transit time thru the device as a function of frequency. The group delay aperture (Δf) can be varied to trade-off resolution and signal-to-noise. The same considerations apply for distortion measurements as electrical length. Group delay is defined by:

$$t_g = \frac{-d\varphi}{d\omega} \cong \frac{-\Delta\varphi}{360 * \Delta f}$$

Time Domain Overview

The Time Domain option of the HP 8753A allows the swept frequency domain information to be transformed into the time domain. This allows the user to view signal components that are separated in time. This is an extremely powerful tool for pulse dispersion and fault location measurements. Let's review the principles behind time domain before looking into these applications in more detail.

With conventional optical time domain reflectometers (OTDRs), an impulse or step is generated and launched into a fiber. The reflected signal is then displayed on the screen versus time or distance. In contrast, the HP 8753A uses a Fourier transform technique to transform the frequency domain data into the time domain. This has the advantage of measuring over broad bandwidths with wide dynamic range and error-corrected accuracy. There are three transform modes available:

1. Lowpass Step Mode. This mode simulates a traditional OTDR by synthesizing the time domain response to a step input. The distance to the discontinuity as well as the nature of the discontinuity (inductive, capacitive, etc.) can be determined.
2. Lowpass Impulse Mode. This mode simulates the response of a device to an impulse (the derivative of the step mode). This mode is very useful for precisely locating discontinuities.
3. Bandpass Mode. This mode simulates the response of a device to an impulse modulated carrier. It is intended for band-limited device measurements that do not have a DC path.

The lowpass modes offer the best resolution but is limited to a maximum alias-free range of 3.333 microseconds, due to the 300 kHz low frequency limit of the HP 8753A. This corresponds to 1 km in air for transmission or 500 meters in air for reflection. The lowpass transform requires that data points be equally spaced to DC (extrapolated). The bandpass mode is therefore required for identifying signals farther out. Alias-free measurement range is a function of the frequency span and the number of points. The measurement range is summarized in Figure 10. The distance nomograph can be used to approximate the maximum measurement range for a given span and number of points, assuming an index of refraction of 1.5. The reflection ranges are shorter due to the double travel path of the signal.

Alias-free time range is given by the following formulas:

$$t_{(max)} = \frac{(N-1)}{\text{Span}} \qquad \text{(Transmission)}$$

$$t_{(max)} = \frac{(N-1)}{2 * \text{Span}} \qquad \text{(Reflection)}$$

Time Domain Overview (Contd.)

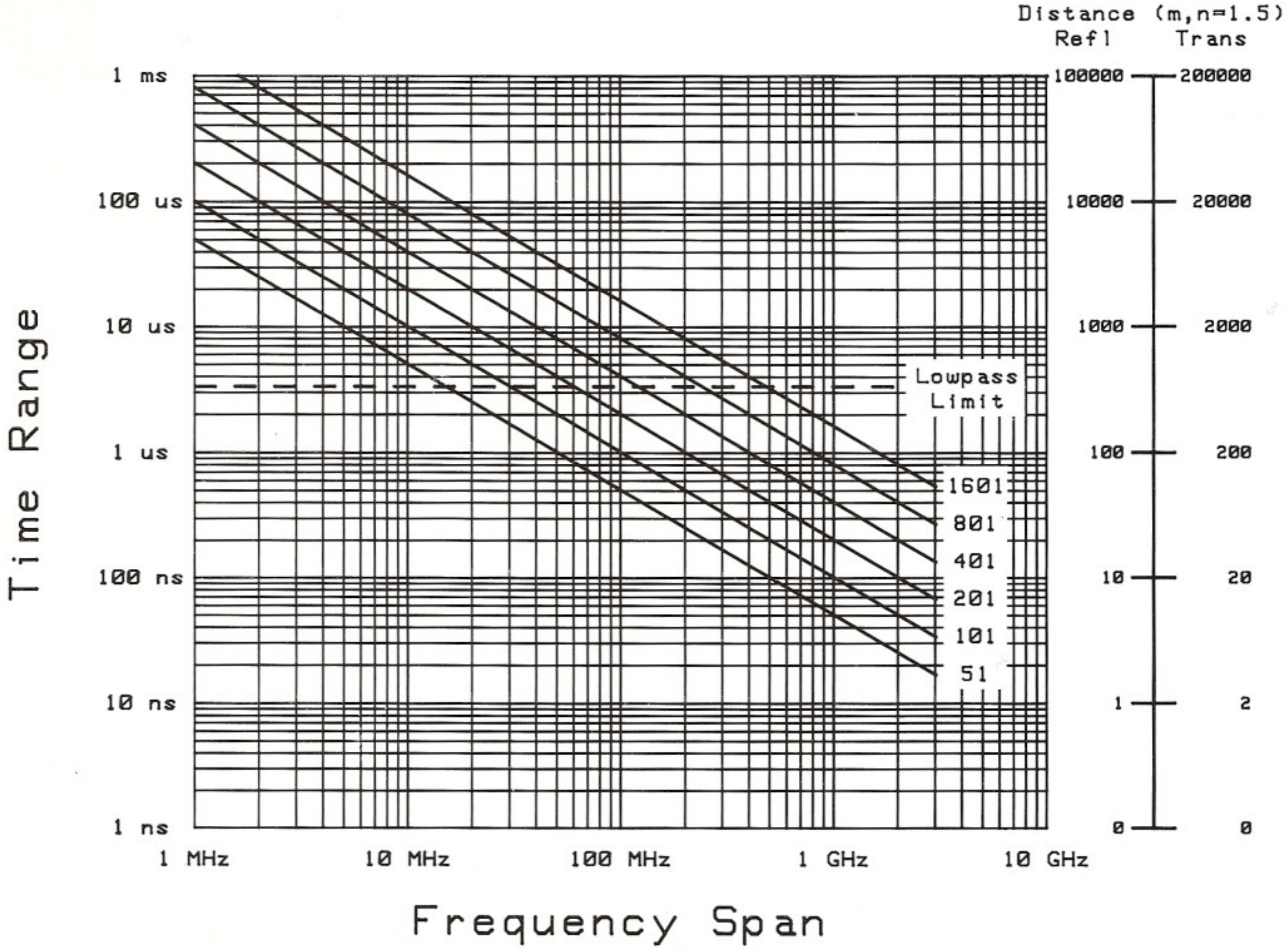


Figure 10. Alias-free Time Domain Range for the HP 8753A

There are two kinds of resolution important in time domain measurements, response resolution and range resolution. Response resolution is defined as the minimum time that two responses of equal magnitude can be separated by and still resolved by three dB. Response resolution is determined by the frequency span of the measurement and the amount of windowing applied to the data. The response resolution of the HP 8753A is summarized by Figure 11. For bandpass measurements use twice the lowpass impulse values. The distance nomograph can be used to determine the resolution for a given span and windowing. The equivalent response resolution for reflection is twice as good as transmission because the actual device responses appear twice as long due to double travel, and can be as good as 3.375 cm for a full span with n=1.5 and minimum windowing.

Transmission time response resolution is given by the following formulas, divide by two for reflection measurements:

$$t_r = \frac{0.45}{\text{Span}} \times \begin{array}{l} 1.0 \text{ Minimum Window} \\ 2.2 \text{ Normal Window} \\ 3.3 \text{ Maximum Window} \end{array} \quad \text{(Lowpass Step)}$$

$$t_w = \frac{0.6}{\text{Span}} \times \begin{array}{l} 1.0 \text{ Minimum Window} \\ 1.6 \text{ Normal Window} \\ 2.4 \text{ Maximum Window} \end{array} \quad \text{(Lowpass Impulse)}$$

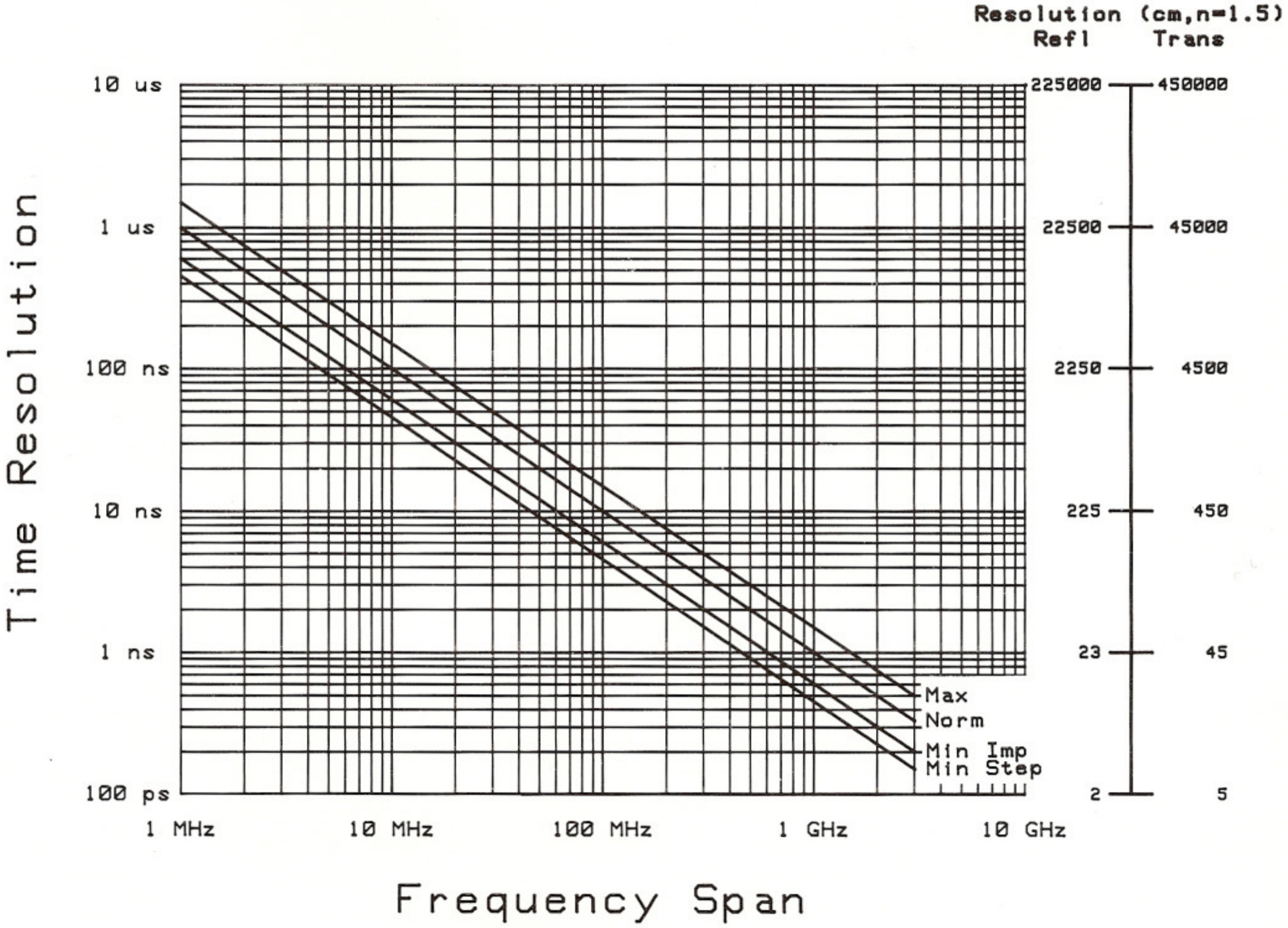


Figure 11. Response Resolution in Lowpass Mode

Range resolution is defined as the minimum time increment that a single response can be resolved to. Range resolution is primarily determined by the source accuracy, and is typically better than a millimeter for most measurements.

In practical applications there is a trade-off between alias-free range and response resolution. Extremely long devices may require two different sweeps to characterize properly. One narrow-band sweep is used to locate the signal in time. The signal is then moved to t=0 by using the **[ELECTRICAL DELAY]** or **[MKR→DELAY]** features. This is done because the HP 8753A does not allow the user to examine signals outside of its alias-free range. Now the signal can be analyzed using a broadband sweep to resolve more detail.

The time domain option also allows us to selectively remove the effects of signals separated in time. This time-filtering technique is called gating, and can be used to improve the accuracy of a measurement, as well as provide new insight into the behavior of networks. Gating is particularly useful in return loss and fault location measurements. An example of a gated return loss measurement is shown in the next section.

Return Loss

The Measurement. Return Loss is a measure of the amount of signal reflected from a device relative to the amount of signal incident on that device. This can be a very important measurement on devices such as couplers, attenuators, and detectors, since large reflections can reduce the amount of power coupled in the forward direction, and, in some cases, interfere with the proper operation of reflection-sensitive devices such as laser diodes.

The Setup. Reflection measurements are possible with the addition of an optical directional coupler. The ratio of the reflected and incident signals yields the return loss of the device. This information can be displayed in a variety of formats, such as LOG, POLAR, and SWR. Calibration is accomplished by connecting a short piece of fiber as a thru and removing the frequency response of the measurement system (excluding the coupler). The directivity of the coupler determines the lower limit available for the measurement. This is important since even a perfectly cleaved fiber exhibits only a 4% refection in air, a 28 dB return loss (14 dB optical)!

Typical Results. Figure 12 shows a swept return loss measurement on an optical detector, an important measurement since reflections can interfere with many optical sources. The output of the detector is terminated in 50 ohms. The optical return loss is 1/2 the displayed value. The ripple is due to the directivity of the coupler beating with the return loss of the device. The effects of the coupler directivity term can be removed using gating.

The flat response in Figure 12 is the return loss measurement after gating. The gated response does not include the ripple caused by the coupler directivity, because it was removed mathematically. The responses must be adequately resolved (far enough apart) for gating to work. Figure 13 shows the time domain response of the detector. The first response at t=0 is the coupler directivity (leakage) and is about 40 dB (optical) down before gating. Gating drops the directivity term from our measurement by more than 15 optical dB.

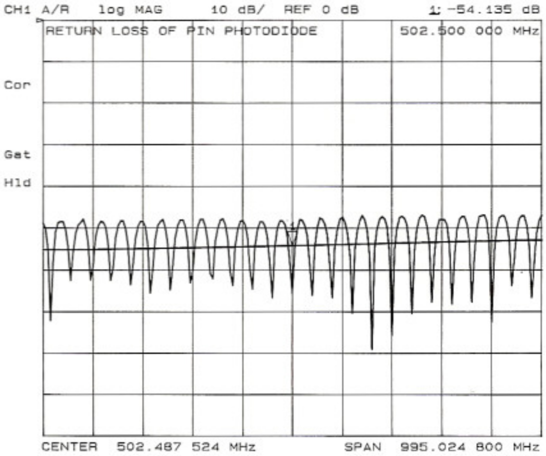


Figure 12. Return Loss of a PIN Photodiode Receiver

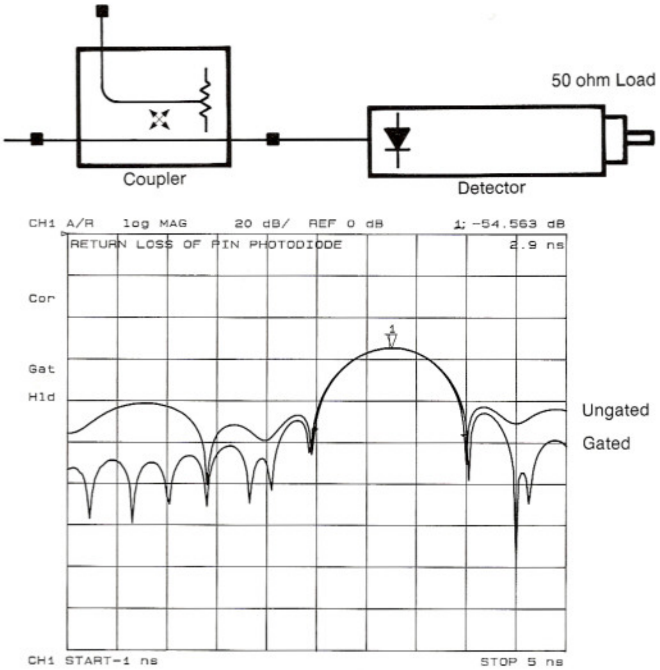


Figure 13. Using Gating to Improve the Return Loss Measurement

The same measurement can be viewed in the Polar format as in Figure 14. The markers can be set to display a variety of information as a function of frequency, such as resistance, return loss, and rho.

Considerations. For sources that are sensitive to back reflection changes, another coupler can be added (or the 2X2 dual directional coupler configuration can be used). In this configuration, the incident optical power is sampled by the forward coupler port, and used as the ratio reference in the B/A measurement configuration. This has the effect of reducing the sensitivity of the measurement to source power variations (improved source match), since both A and B are affected equally. Of course, an additional O/E converter is required for this configuration.

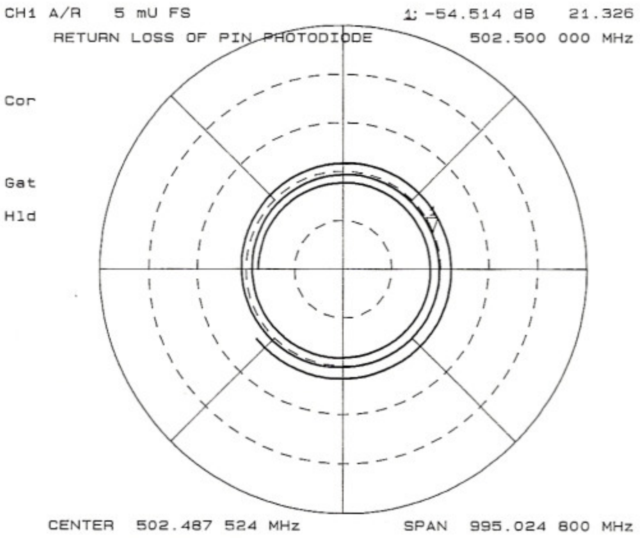


Figure 14. Gated Return Loss of a PIN Photodiode Receiver in the Polar Format

Pulse Dispersion and Transient Analysis

The Measurement. Pulse dispersion is a measure of the spreading exhibited by a pulse in a linear device or system primarily due to the intermodal and intramodal effects of the fiber waveguide itself. This is an important measurement because dispersion can limit the systems' ability to transmit high frequency modulation. Pulse dispersion is a graphic way of measuring bandwidth in the time domain. When a step excitation is used, the same measurement allows us to graphically view the transient response of components and systems.

The Setup. Pulse dispersion measurements and transient analysis are typically performed in the transmission configuration and in the REAL format for easy identification of the half power points. The lowpass transform mode is typically used for highest resolution. A marker is placed on the top of the impulse with the automatic search function of the HP 8753A and established as the delta marker reference. The impulse width is then measured using the automatic width function, and dispersion calculated by:

$$\Delta t_{(DUT)} = \sqrt{\Delta t_{(out)}^2 - \Delta t_{(in)}^2}$$

Where: $\Delta t_{(DUT)}$ = Total pulse dispersion of DUT

Typical Results. Figure 15 demonstrates a total dispersion measurement on a roll of multi-mode fiber using the lowpass impulse transform mode. The top pulse is the equivalent impulse response of the system as measured at the Full Width Half Maximum (FWHM) points, and was measured after calibrating with a thru. The bottom pulse is the equivalent output pulse of the cable, shifted to t=0 with the **[ELECTRICAL DELAY]** feature. The pulse spreading is primarily due to modal dispersion. The total dispersion of this cable is 550 picoseconds, corresponding to a normalized value of 366 ps/km.

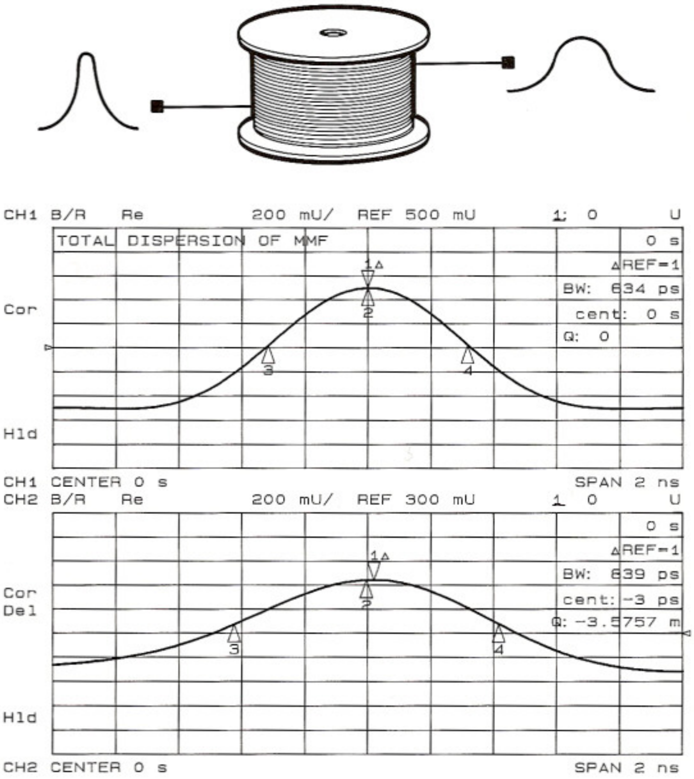


Figure 15. Total Dispersion Measurement on a 1.5 km Roll of Multi-Mode Fiber

Pulse Dispersion and Transient Analysis (Contd.)

Another multi-mode cable measured over the same frequency range demonstrates the differential mode delay effects in the time domain, as shown in Figure 16. Two propagation modes are clearly visible in these plots. This frequency selectivity is obviously a powerful feature that allows us to diagnose how a device or system will perform over specific frequency ranges. For example, this measurement allows us to see that the third harmonic of a 300 MBPS digital train may be adversely delayed or attenuated by the mode effect in this cable.

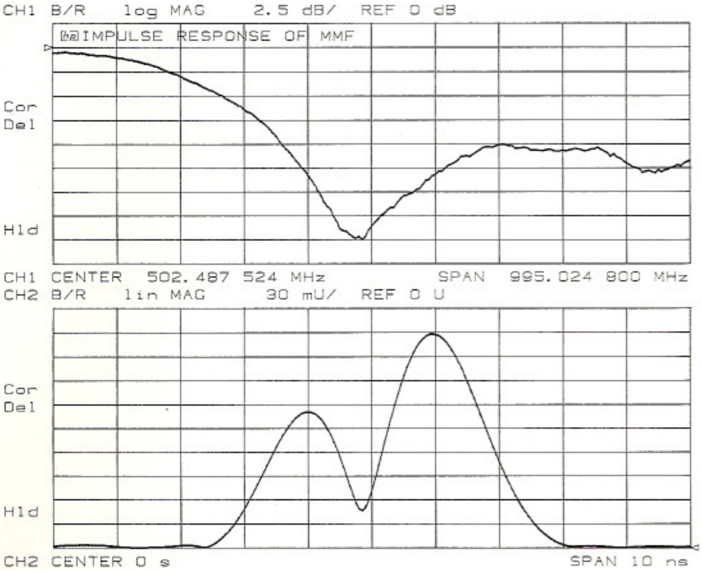


Figure 16. Impulse Response of MM Fiber Showing Two Distinct Modes

The lowpass step mode is useful for examining the baseband transient response of devices operating in their linear region, such as amplifiers, detectors, or entire systems. Figure 17 demonstrates the step response of the transceiver system. The system gain is evident from the magnitude information. The system equivalent risetime is 1146 picoseconds as calculated by the following equation:

$$t_{r(DUT)} = \sqrt{t_{r(out)}^2 - t_{r(in)}^2}$$

Where: t_r = Equivalent risetime of DUT

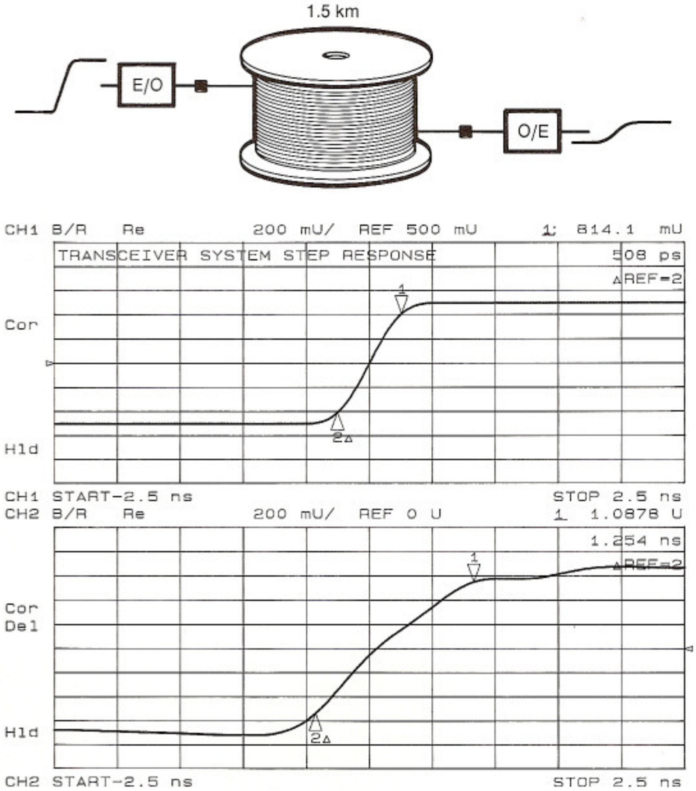


Figure 17. Step Response of the Converter-Cable-Converter System

Fault Location

The Measurement. With the time domain option, the frequency domain reflection information can be transformed into the time domain to display the response of faults (discontinuities) separated in time. This capability becomes an important troubleshooting tool for identifying faulty components in a system, such as connectors or couplers. The powerful gating feature also allows us to selectively remove the effects of undesired error signals in our measurement. Since the network analyzer measures in the frequency domain with a swept CW source, this system also has the advantage of having no close-in "blind spot," a typical limitation with conventional OTDRs.

The Setup. The measurement is made in the reflection configuration. The fiber end is terminated with matching gel to eliminate re-reflections. A velocity factor of 0.333 was entered into the analyzer to adjust for slowing and the double-travel time through the fiber.

Figure 18 shows a fault location measurement on a series of two 1.5 km rolls of multi-mode fiber using the bandpass transform mode. Bandpass was used because it allows us to achieve the longest alias-free range. In this case, a 25 MHz frequency span was used with 801 display points to obtain a 30 µsec alias-free range (refer to Figure 10). The connector discontinuities are clearly visible in this display, with Marker 1 at the end of the first cable.

Figure 19 shows a measurement of a 5 meter patchcord followed by a 17 meter fiber section using the lowpass impulse transform mode. The lowpass impulse mode is a convenient mode for fault location, because it provides the best available response-resolution, and because the top of the response is easily located. In this case, a 1 GHz frequency span was used with normal windowing to obtain about 20 cm of response resolution (refer to Figure 11). Marker 2 is positioned at the response of connector at the end of the 5 meter patchcord section.

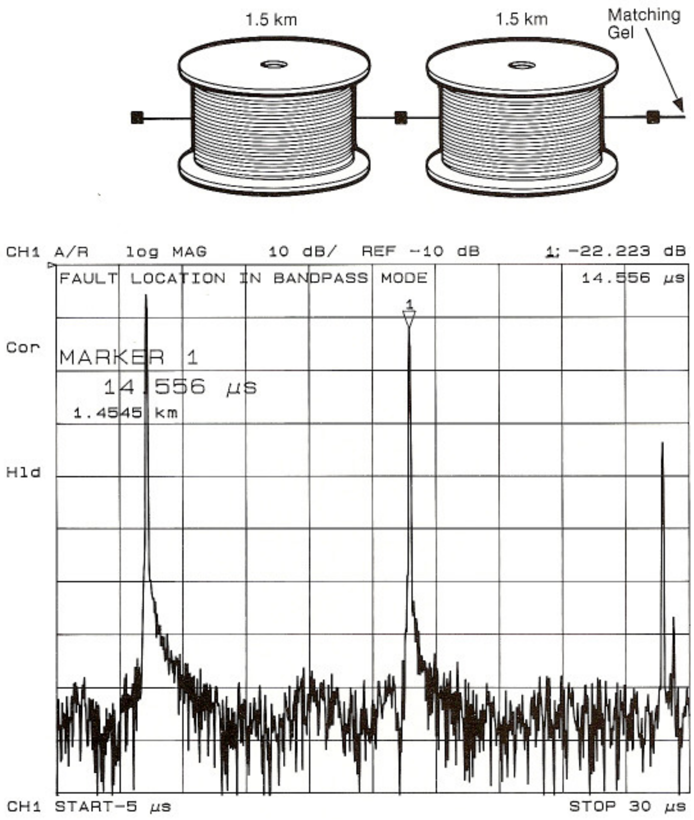


Figure 18. Fault Location in the Bandpass Mode

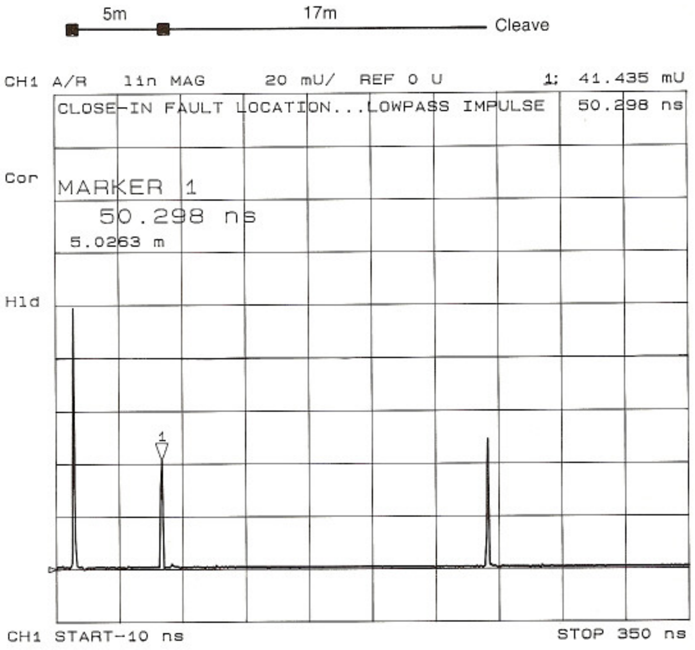


Figure 19. Fault Location in the Lowpass Impulse Mode

Fault Location (Contd.)

To demonstrate even better resolution, we can measure a 16 cm fiber section, as in Figure 20. A 1 GHz span and minimum windowing provides us with response resolution of about 10 cm. The fiber cleave is left unterminated, allowing us to view two responses of approximately the same magnitude. Using 3 GHz convereters would allow us to view signals even closer together.

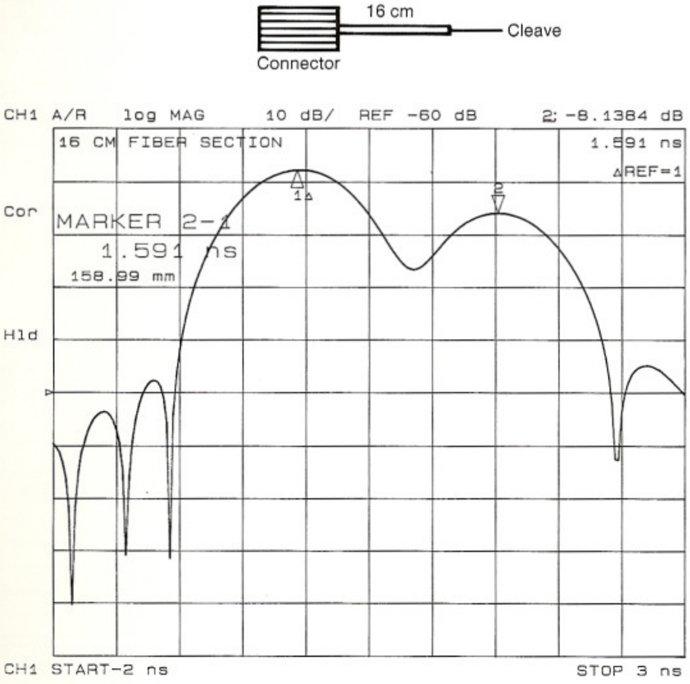


Figure 20. Measurement of 16 cm Section of Fiber

Summary

In conclusion, the network analyzer is a valuable tool for characterizing electrical components, particularly within the frequency range of modern high-speed fiber-optic systems. Both magnitude and phase information can be obtained for complete network characterization in transmission and reflection.

With the addition of suitable optical sources, receivers, and accessories, the same capabilities can be extended to characterization of optical components and systems.

The time domain feature provides valuable insight into the performance of components and networks, and adds new capabilities for measuring pulse dispersion and fault location.

The system described in this note provides a versatile and cost-effective solution for many of the emerging photonic measurement problems. As systems move to higher bit rates, as performance demands increase, more and more of these problems will see the light of frequency domain optical analysis.

Appendix A

For more information on the specific optical converters and accessories described in this application note, contact these manufacturers. Equivalent devices are available from other manufacturers.

Optical Converters

Models:	Single-mode E/O Converter	AQ-1332
	O/E Converter	AQ-1442

Ando Corporation (U.S. Headquarters)
480 Oakmead Parkway
Sunnyvale, CA
(408) 749-8163

Ando Europe B.V. (Europe)
"Vijverdam" Dalsteindreef 57
1112 XC Diemen, The Netherlands
020-981441

Ando Electric Co., LTD. (Overseas Sales)
19-7, Kamata 4-chrome
Ota-ku, Tokyo, 144 Japan
(03) 733-1151

Optical Couplers and Splitters

Model:	1X2 Directional Coupler	DC-09

Kaptron Inc.
3460 W. Bayshore Rd.
Palo Alto, CA 94303
(415) 493-8008

Mode Scramblers

Corning Mode Scrambler

Corning
Telecommunications Products Division
Corning Glass Works
Corning, NY 14831
(607) 974-4411

For information about Hewlett-Packard products and services, telephone the local Hewlett-Packard sales and support office listed in your telephone directory. Or write to the appropriate address listed below.

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Hewlett-Packard
5201 Tollview Drive
Rolling Meadows, IL 60008

Hewlett-Packard
2000 South Park Place
Atlanta, GA 30339

Hewlett-Packard
5161 Lankershim Blvd.
North Hollywood, CA 91601

Canada
Hewlett-Packard (Canada) Ltd.
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Mississauga, Ontario L4V 1M8
Tel: (416) 678-9430

United Kingdom
Hewlett-Packard Ltd.
King Street Lane
Winnersh, Wokingham
Berkshire RG11 5AR
Tel: 734/78 47 74

France
Hewlett-Packard France
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2, avenue du Lac
91040 Evry Cedex
Tel: 1 60 77 83 83

German Federal Republic
Hewlett-Packard GmbH
Hewlett-Packard-Strasse
Postfach 1641
D-6380 Bad Homburg
West Germany
Tel: 06172/400-0

Italy
Hewlett-Packard Italiana S.p.A.
Via G. Di Vittorio 9
1-20063 Cernusco Sul
Naviglio (Milano)
Tel: 02/92 36 91

Benelux and Scandinavia
Hewlett-Packard S.A.
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P.O. Box 999
NL-1183 AG Amstelveen
The Netherlands
Tel: (31) 20/43 77 71

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Hewlett-Packard S.A.
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Operations
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Paradissos-Amarousion, Athens
Greece
Tel: (30) 682 88 11

South and East Europe, Africa
Hewlett-Packard S.A.
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CH-1217 Meyrin 2, Geneva
Switzerland
Tel: (41) 22/83 12 12

Japan
Yokogawa-Hewlett-Packard Ltd.
29-21 Takaido-Higashi, 3 Chome
Suginami-ku, Tokyo 168
Tel: 03 (331) 6111

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Hewlett-Packard Asia Ltd.
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Wanchai, Hong Kong
G.P.O. Box 863, Hong Kong
Tel: (852) 5-8330833

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Hewlett-Packard Australia Ltd.
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Blackburn, Victoria 3130
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